IN THE UNITED STATES PATENT & TRADEMARK OFFICE
Before the Primary Examiner

In re Application of:
HAROLD R. KAUFMAN et al. Group Art Unit: 2879
Serial No. 09/848,644
Filed: May 3, 2001 Examiner: Holly R. Harper
For: IMPROVED HALL-CURRENT ION SOURCE

Attorney Docket No. 353-07

Hon. Commissioner for Patents
P. O. Box 1450
Alexandria, VA 22313-1450

DECLARATION OF HAROLD R. KAUFMAN

HAROLD R. KAUFMAN, being duly sworn, deposes and states as follows:

1. I am one of the named inventors in the above-identified application.

2. I have read the Office Action mailed June 19, 2003 and the prior art references cited by the Examiner. I am the named inventor in U.S. Patent No. 5,763,989 cited by the Examiner.

3. (a) The phrase "increase the area of said surface by approximately one-half" is not indefinite as used in our specification or claims. The quoted phrase has reference to the "electron-collecting surface" which is defined in our specification (para. 0040) as "the anode surface readily available and utilized for electron collection". The next sentence in para. 0040 further defines this surface with the statement "In contrast, to reach surfaces of anode 18 other than surface 28, electrons must cross additional magnetic field lines, diffuse farther from the discharge region, or both".

(b) Using the definition in our specification, the area of the prior-art electron-collection surface is surface 28 of anode 18 for the end-Hall ion source shown in Fig. 1 (see para. 0040). The area of the prior-art electron-collection surface is shown as surface 60 of anode 50 for the closed-drift ion source shown in Fig. 2 (see para. 0046).

(c) The increased area of the electron-collection surface in the end-Hall embodiment shown in Fig. 3 is shown in detail in Fig. 3a as areas 73, 74 and 75 (see paras. 0055 and 0056). The increase in area is created by one or more protrusions and/or one or more recesses and is shown clearly as the sum of areas 73, 74 and 75 which exceeds the prior-art area of surface 28 in Fig. 1.

(d) The increased area of the electron-collection surface in the closed-drift embodiment shown in Fig. 9 is shown in detail in Fig. 9a as area 122 (see para. 0083). The increase in area is created by protrusions and/or recesses and is shown clearly as area 122 exceeding the prior-art area of surface 60 in Fig. 2.

4. (a) The Yoshida patent (U.S. Pat. No. 4,846,953) describes an ion source of the duoplasmatron type (col. 1, lines 23-25). The duoplasmatron ion source is an electrostatic ion source in which the acceleration of ions is accomplished electrostatically (see para. 0001 of our specification). The present invention uses a Hall-current ion source in which the acceleration of ions is accomplished electromagnetically. The Yoshida patent thus refers to a different type of ion source than is used in the present invention.

(b) The Yoshida ion source generates an ion beam that passes through electrode 8 and continues to the right, with the ion beam target assumed to be farther to the right. The electrons reaching anode 4 come from cathode filament 3 and thus approach anode 4 from the left, opposite to the direction of the target. There is therefore no coating from the target that prevents collection of these electrons by anode 4. In electrostatic acceleration, an acceleration-deceleration approach is used that prevents electrons from flowing from the ion beam back to the anode in the discharge region.

(c) The duoplasmatron source is also described by Keller in Chapter 7 of "The Physics and Technology of Ion Sources", John Wiley & Sons (1989), pp. 158-161. A copy of this chapter is attached hereto. The only significant difference between Fig. 7.8 on p. 159 and Fig. 1 of Yoshida is the inclusion of sputtering electrode 6 in the latter. Referring to p. 158 of the Keller chapter, the "contour" in the anode to which the examiner appears to be referring is called an "expansion cup". The expansion cup functions as part of the electrostatic acceleration process, and has nothing to do with the protection of part of the anode from the deposition of target material. What the examiner refers to as a "contour" is thus on the opposite side of the anode from the "electron-collection surface" as defined in our specification.

(d) The ion source of Yoshida is a different type of ion source from that described in our specification. In Yoshida's ion source, the electrons approach the anode from the direction opposite to the target, and

the "contour" referred to by the examiner pertains to the ion acceleration process instead of the collection of electrons. Thus, the "contoured" surface referred to by the examiner in Yoshida is not pertinent to the present invention.

5. The examiner refers to the Kaufman patent (Fig. 11) as showing an anode that is contoured to increase surface area. However, the area referred to in our present claims is not the area of the anode but rather is the area of the "electron-collecting surface", which is defined in para. 0040 of our specification. The electron-collecting surface of the anode in Fig. 11 of the cited patent is the annular area exposed when viewing the ion source from the right (the location of the target). Anode areas both inside and outside the anode that are not included in this annular area can be reached only by crossing additional magnetic field lines; hence, such anode areas cannot be included in the "electron-collecting surface". The inside of the anode also is not accessible to discharge electrons because of the high pressure therein and the small access holes. It should be clear from col. 6, lines 33-43, that discharge electrons do not reach the interior of the anode in Fig. 11 during normal operation. Further, the increase in area to which the examiner is apparently referring constitutes baffles 50 which serve to circumferentially distribute the working gas (see col. 5, lines 60-64).

6. The present invention is not described in either of the cited references. Further, the present invention would not be obvious to a person of ordinary skill in this art based upon the teachings of such cited references.

7. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that

willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Date: 19 Aug 2003

Harold R Kaufman
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The Physics and Technology of Ion Sources

Edited by

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Berkeley, California

1989

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7

High-Current Gaseous Ion Sources

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Both terms marking this group of high-current ion sources need some specific explanations. *High current* strictly speaking means that for the beams delivered by these sources space-charge phenomena are a major concern. In absolute numbers, the ion beam currents may vary between 10 mA and 100 A, but still the essential features of the sources are similar enough to include them all in one group. *Gaseous* here takes on a rather broad meaning, including vapors of pure or compound materials. In reviewing such sources, one should distinguish between the plasma generator or source proper, and the extraction system; both together may then be called *ion gun* for complete clarity. The distinction is needed for the simple reason that different plasma generators can be used with identical extraction systems, and different extraction systems can well be used on a given plasma generator.

The present chapter is concerned primarily with plasma generators, leaving a thorough discussion of extraction systems to Chapter 3. There is one stringent condition that both of these two units must fulfill to enable a complete ion gun to work: The plasma generator must provide a plasma of the correct density to match a given extraction system; or, seen from the other side, the extraction system must be designed in such a way that it requires a plasma density value to be created by the generator that is within the working range of the latter.

To facilitate a comparison between the beam intensities that will be reported from various ion sources in the following, it is best to use normalized beam current values. This normalization takes into account that, according to the Child-Langmuir law [1, 2], heavier ions are harder to extract than lighter ones, see the chapter on ion extraction, Eqs. (1) and (2). The conversion between absolute current I and

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normalized current I_n is done according to

$$I_n = I\,(A/\zeta)^{1/2}$$

where A is the atomic mass number and ζ is the charge state; and to clearly mark normalized currents their units (mA) will be put in parentheses throughout the present chapter.

Historically, high-current ion sources have been developed for several completely different purposes: neutral injection to heat magnetically confined fusion plasmas [3], space propulsion [4], and materials treatment including ion implantation [5] at first, and in the last decade supplying particle accelerators with ions for fundamental research and inertial confinement fusion projects [6]. All of these aims have imposed quite different principal requirements on the ion sources, such as power efficiency, fuel efficiency, reliability, ample choice of the ion species, and beam quality. The dominance of one of these criteria over others, together with the common fact that a design philosophy is rarely changed if the device once had some degree of success, has led to fairly differentiated source types, but still there are many similarities between them.

The main features that are common to all high-current sources treated here are the following: The ions are created by electron-impact ionization of a gaseous medium, forming a plasma; this plasma has a considerable width, several centimeters at least and up to tens of centimeters; the electron density is about 1×10^{13} cm^{-3} and is homogeneous over that part of the plasma from which ions are to be extracted; the ion temperature usually lies well below 1 eV [7]. Quite frequently discharges are employed that are sustained by a thermionic cathode (often erroneously called *arc discharges*), but also rf discharges are well suited to create a plasma and preferred if electrode corrosion would be of serious concern.

All modern high-current ion sources employ magnetic fields to confine the plasma and enhance the ionization rate per electron, and here the so-called minimum-B configuration [8] is quite advantageous: Stable plasma containment over a large density range can be achieved only if the magnetic field lines are curved away from the region of higher plasma density, thus leaving a zone of low-field values at the center of the discharge chamber. Such configurations, see Figure 7.1, can be realized in the form of a linear multipole (usually created by strong permanent magnets), an axial cusp arrangement (generated by permanent ring magnets or coils with antiparallel current flows), a yin/yang or baseball current loop, or simply as a diverging axial field produced by permanent magnets or a single coil. In the latter case, the plasma volume is mechanically confined to a region on one side of the coil center plane only.

One family of sources makes use of a two-stage discharge where the plasma of the first discharge stage acts as a plasma cathode and yields primary electrons for sustaining the main stage [11–13]. Such an arrangement leads to very good gas and power efficiencies but is more likely to suffer from plasma oscillations, in turn.

In the following, several sources are presented which are typical or outstanding specimens of their group. It should be kept in mind that the performance data

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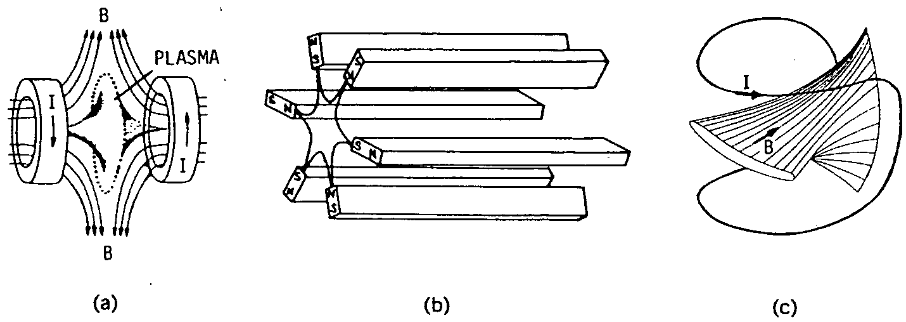


Figure 7.1 Minimum-B magnet configurations. (*a*) Monocusp. After Ref. 8, © 1976 Academic Press. (*b*) Multicusp, here a linear sextupole created by permanent magnets. From Ref. 9, © 1982 VDI Bildungswerk. (*c*) Yin/yang or baseball device. After Ref. 10, © 1970 Vieweg Verlag.

reported here are not always the real limits for the individual sources but in many cases are imposed by other conditions such as available power supplies or simply the given project goals. True beam current and brightness limits for all ion source types are determined by the physics of the extraction process.

1 SOURCES WITH SINGLE-STAGE DISCHARGE

An example of a very simple but reliable source is the so-called *Penning* source developed for a heavy-ion fusion project [14], see Figure 7.2. This high-current source should not be mistaken for the PIG (Penning Ionization Gauge) source for

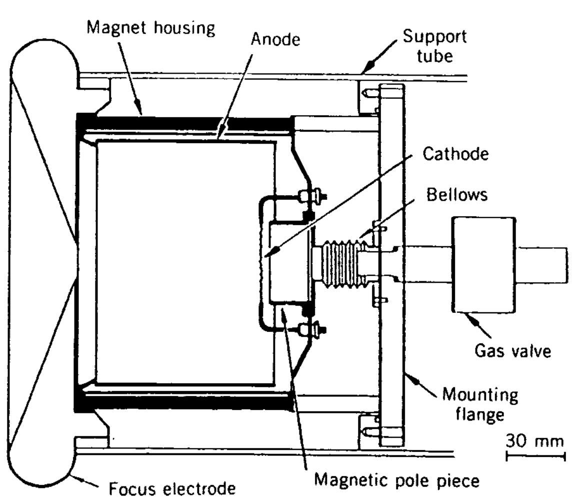


Figure 7.2 Penning high-current ion source. The beam is extracted to the left; the "focus electrode" is usually called the outlet electrode in this chapter. After Ref. 14, © 1979 IEEE.

multiply charged ions, which is treated in a separate chapter. The high-current Penning source is equipped with permanent magnet rods that are disposed around the anode cylinder and create an axial magnetic field diverging from the pole piece near the cathode toward the outer source border on the extraction side. Xenon and mercury have been used as feed materials, and xenon ion currents of 30 mA, or 344 (mA) normalized, were obtained from a 6.7-cm^2 single-aperture extraction system at 100 kV and with a discharge power as low as 150 W. As required by the intended application, in the quoted work the discharge was pulsed with duty cycles of about 0.001. Other sources of this type are operated under dc conditions as well [15].

The monocusp ion source, see Figure 7.3, was developed for a neutron generator, optimizing the discharge for high deuteron yield as well as for high gas efficiency [16]. The limitation of the magnetic field to one ring cusp and the careful positioning of the anode ring, just touching those field lines that pass through the edges of the cathode filaments, effectively minimize plasma losses. Further, there exist two electron populations in the discharge volume, with quite different mean energy values. By choosing a suitable discharge voltage one of these values can be adjusted to the maximum cross section for ionization of H_2 molecules, while the other one is much lower, favoring the dissociation of H_2^+ molecular ions. The disadvantage found with this source is the pronounced radial variation of the plasma density which severely limits the plasma size useful for extraction. Thus, only

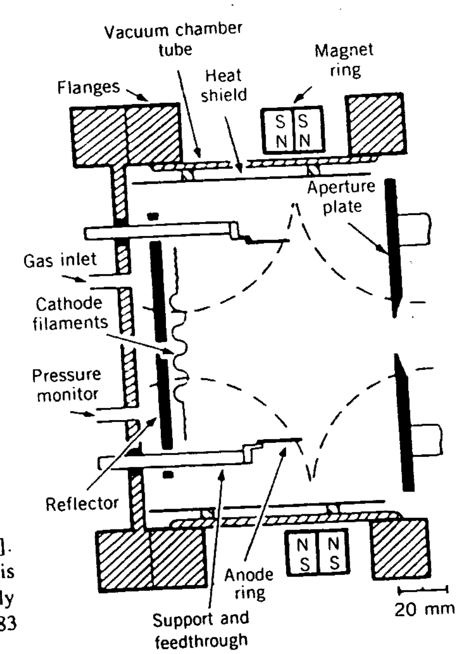


Figure 7.3 Monocusp ion source [Ref. 16]. Broken lines: magnetic field lines. The beam is extracted to the right; the "aperture plate" is usually called the outlet electrode in this chapter. © 1983 AIP.

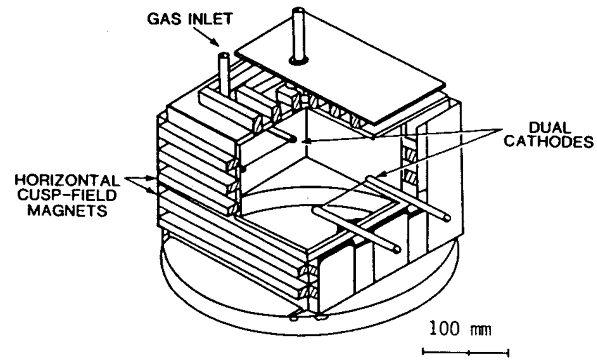


Figure 7.4 Multicusp ion source [Ref. 18]. The beam is extracted in the downward direction.

single-aperture extraction systems can be applied to this plasma generator. Total deuterium ion currents up to 800 mA dc with about 60% deuterons, or 1385 (mA) normalized, are reported for 200 kV extraction voltage and 6 kW discharge power.

Multicusp sources are the ones most frequently used in the class with a single discharge stage, presently under discussion, for one reason: Their detailed mechanical layout is far less critical than that of the two preceding source types. Any discharge vessel lined with permanent magnets will work satisfactorily in that it can yield a plasma with the required properties. This simplicity has led to the nickname "bucket source" for such plasma generators [17]. With the simplest version, see Figure 7.4, nearly the entire discharge chamber is lined by magnets and acts as anode; primary electrons are created by thermionic emission from filaments forming the cathode, and only the outlet electrode is biased close to cathode potential. The effective anode area is determined by the electron loss zones and amounts to the entire length of all the cusp lines together, times twice the electron gyro-diameter, typically a few millimeters [19]. The source according to Ref. 18 delivers 100 mA dc total hydrogen ion current—about 122 (mA) normalized—at 100 kV from a single-aperture extraction system with 1-cm^2 outlet area.

Other multicusp sources are more refined, to obtain special plasma conditions desired for the intended application. As an example, by introducing a magnetic dipole field inside the discharge chamber, across the plasma column, electron populations of different energies can be separated, favoring the production of protons in the case of hydrogen feeding gas [20]. This configuration is sometimes called a "picket-fence" [21].

Minimizing the power requirements for a given ion current output led to a source design, the *Kaufman source*, where the anode is composed of narrow metal strips positioned between two adjacent magnet pole pieces [15], see Figure 7.5. Such a configuration forces the discharge electrons to transversely cross the magnetic field lines and at higher densities invariably causes plasma oscillations to be excited, precluding the formation of ion beams with low divergence. In fact, quoted diver-

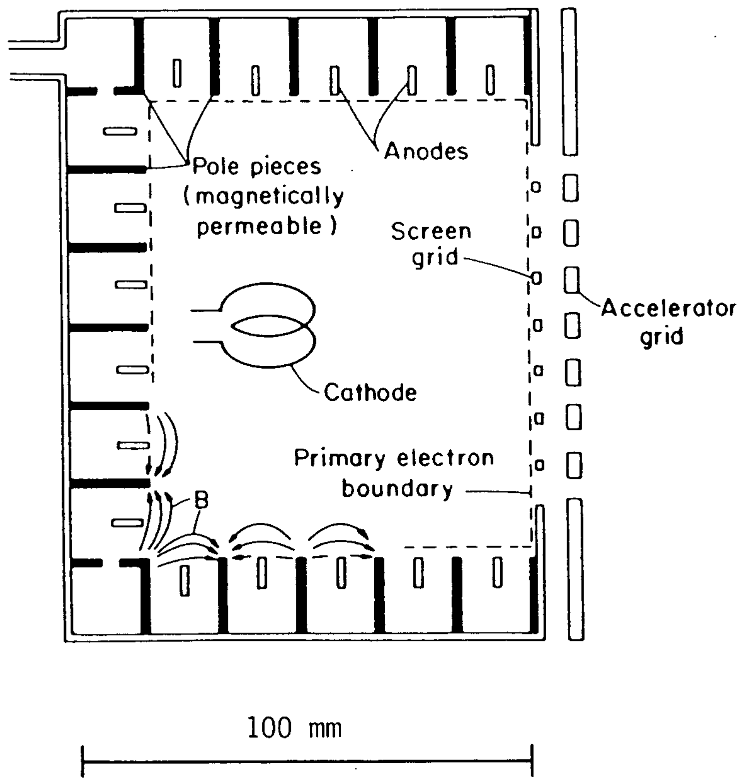


Figure 7.5 Multicusp ion source for industrial applications [Ref. 15]. As stated in the reference, the actual source dimensions may be varied widely; the scale shown gives an idea of a possible size. The beam is extracted to the right; the "screen grid" is usually called the outlet electrode in this chapter. © H. R. Kaufman.

gence values for this source are in the order of 10°, rather than 1° as customary for accelerator sources, but for applications such as ion beam milling through masks or sputter deposition this is not harmful at all. A typical argon ion current per extraction hole is 1 mA dc—6.3 (mA) normalized—at 2 kV, and such sources may have 1000 and more outlet apertures; only 540 W discharge power is then needed to sustain a plasma of the matching density.

Another specimen is the reflex discharge multicusp source CHORDIS [22], featuring the cylindrical anode alone lined with magnets and both end plates of the discharge chamber on or close to cathode potential, see Figure 7.6. While the electrons are well contained in this configuration, the ions will be accelerated towards both end plates. This may even favor the extraction process, but certainly leads to more ion losses on the other side of the source, to be paid for by higher discharge power than with other multicusp sources. The technical benefit lies in

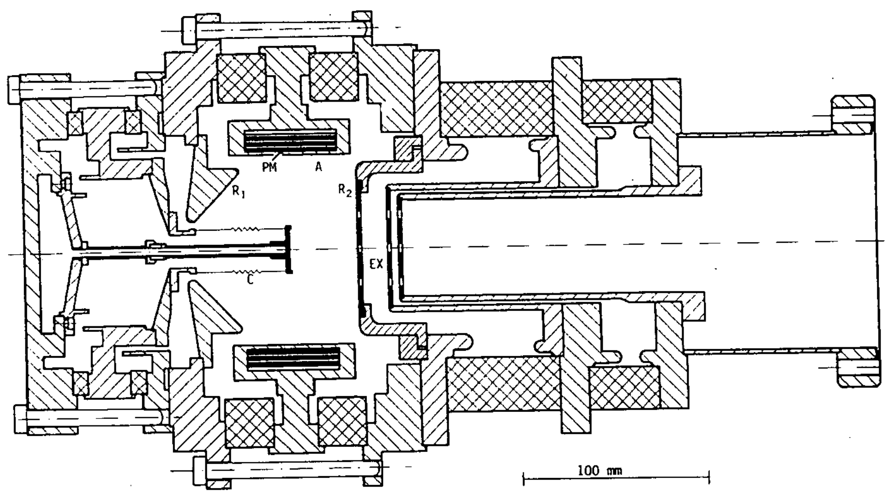


Figure 7.6 Cold version of CHORDIS, for gases [22]. A, anode; C, cathode filament; EX, accel-decel extraction system; PM, permanent magnet; R_1, R_2, reflector electrodes; R_2 acts as outlet electrode as well. The beam is extracted to the right.

the possibility to install more complex structures on the rear side of the source, in order to process materials other than gases. One example of an ion beam obtained from the cold source version is 71 mA dc of xenon ions, 814 (mA) normalized, at 50 kV, out of 2 cm^2 outlet area at 1.8 kW discharge power.

Other multicusp sources are presented in Ref. 23, describing the ion gun for a spallation neutron source project, and Refs. 7 and 24, regarding neutral injection sources for magnetic confinement fusion projects that can deliver several tens of amperes beam current during 10 second pulses at typically 80 kV from about 150 cm^2 total outlet area.

As previously mentioned, the discharge can also be maintained by rf power with typically 2 MHz frequency [25], rather than by a dc voltage between a thermionic cathode and an anode. The problem with rf discharges lies in the varying plasma impedance, making a careful matching to the rf coupling antenna imperative. One example of a successful source model uses inductive coupling by a water-cooled antenna disposed around the cylindrical quartz discharge vessel [26], see Figure 7.7. A 10-cm-diameter source of this type is able to generate hydrogen ion current densities of 200 mA/cm^2 with about 85% protons, at 3.2 kW discharge power. The outcoming beam then has about 2° divergence. The antenna may also be inserted into the discharge chamber, allowing the walls to be lined with permanent magnets to create a multicusp array [27]. With microwaves of 2.45 GHz frequency, capacitative coupling into a resonator of adjustable dimensions appears to be another suitable technique to create a plasma of the needed density [28]. Microwave sources in general are separately treated in another chapter of this book.

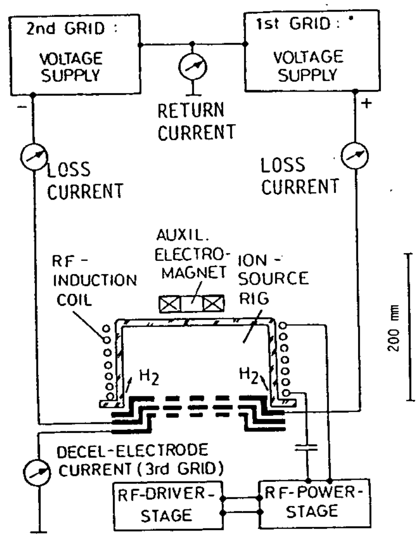
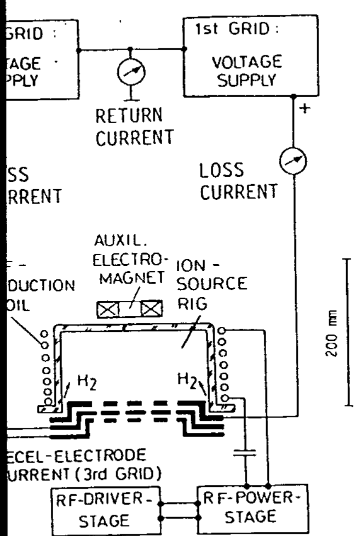


Figure 7.7 RIG 20 ion source with rf discharge [26]. The beam is extracted in the downward direction. The "first grid" is usually called the outlet electrode in this chapter.

2 SOURCES WITH TWO-STAGE DISCHARGES

The most important pioneer work in the development of high-current ion sources was performed with duoplasmatrons [11, 12] and duopigatrons [13], that is, two-stage discharges. With both, a discharge is maintained at relatively high pressure (about 3×10^{-2} Torr) and low voltage (typically 10 V) between a thermionic cathode and an intermediate electrode, acting as primary anode. The plasma is then guided by a strong axial magnetic field through an aperture within the intermediate electrode into the second discharge chamber, where the discharge runs at much lower pressure (about 2×10^{-3} Torr) and higher voltage (typically 80 V), between the intermediate electrode, now acting as cathode for this stage, and the main anode. In the case of a duoplasmatron, see Figure 7.8, the plasma created in the second stage flows out through a small aperture in the anode and expands into a third chamber, the so-called expansion cup [30]. Duopigatrons are modified duoplasmatrons, with largely increased anode aperture and the end wall of the expansion cup, functioning as source outlet electrode for the extraction system, biased negatively with respect to the anode potential. This arrangement causes the electrons of the second discharge stage to be reflected between outlet and intermediate electrode, thus leading to a reflex discharge with much better power and gas efficiencies than found with the duoplasmatron. The magnetic field that guides the plasma from the first into the second chamber expands toward the outlet electrode and thus the second stage of the duopigatron closely resembles the Penning high-current ion source mentioned above. An advanced duopigatron is shown in Figure 7.9. It yields, for example, 98 mA dc of 35 keV xenon ions—



GE DISCHARGES

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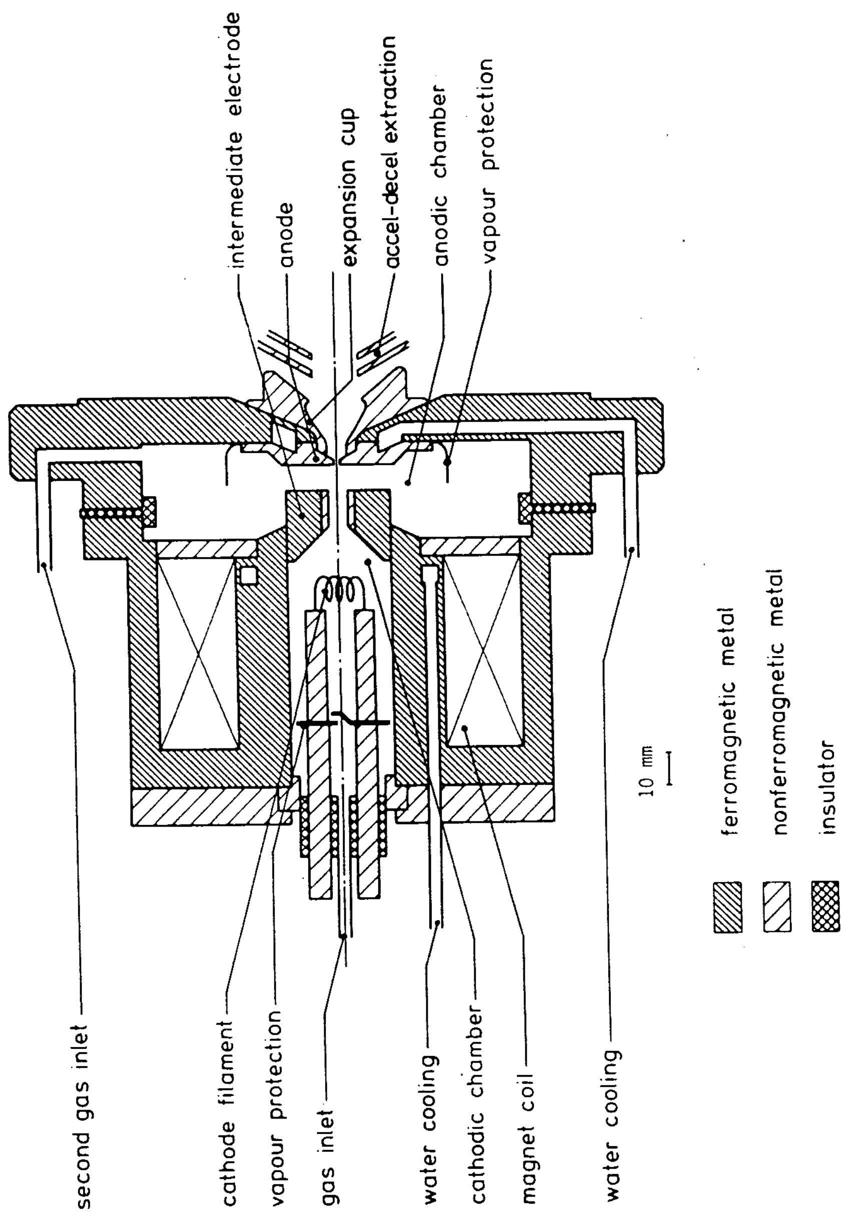


Figure 7.8 Duoplasmatron with expansion cup [Ref. 29]. The beam is extracted to the right. The anode and expansion cup together act as the outlet electrode. Reprinted by permission of the author and publishers. © 1979 Gordon and Breach Science Publishers, Inc.

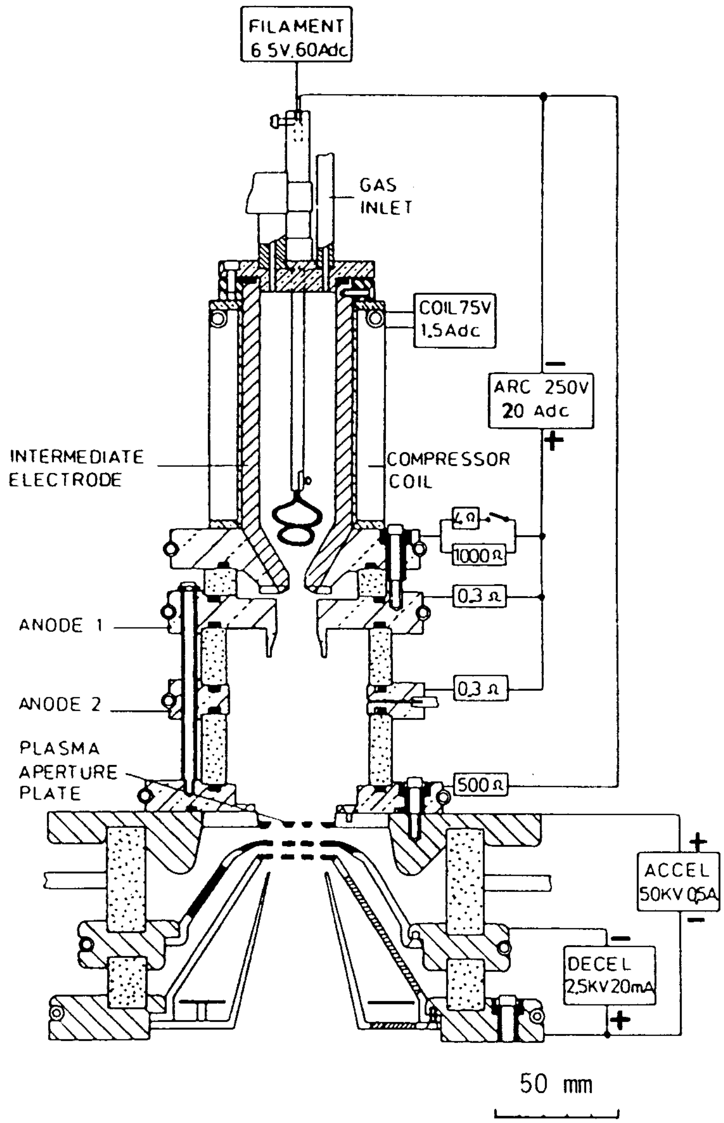
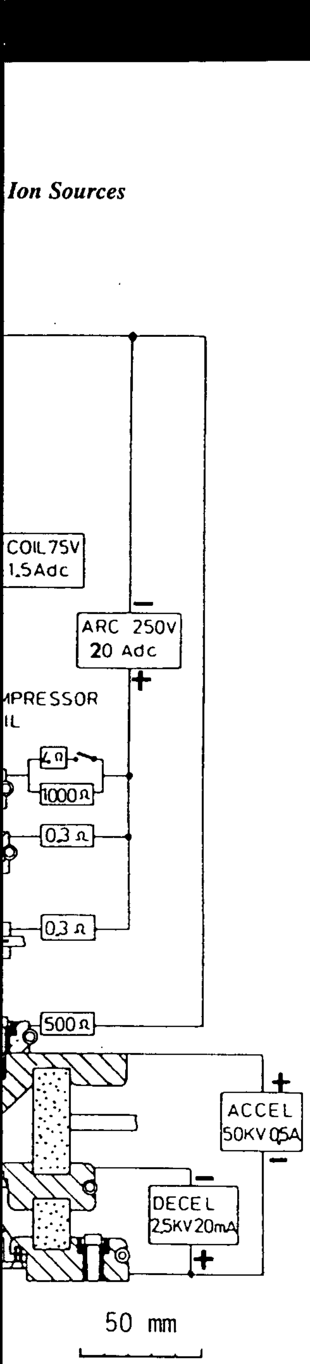


Figure 7.9 Duopigatron [Ref. 31]. The beam is extracted in the downward direction. The "plasma aperture" is usually called the outlet electrode in this chapter. © 1980 IOP Publishing Ltd.

1123 (mA) normalized—from 1.4 cm^2 aperture area at 520 W discharge power [31]. Another outstanding example is the MATS III source, yielding 1500 mA of 20 keV hydrogen beam (70% protons, 25% double, and 5% triple ion molecules) out of 8 cm^2 aperture area at 4 kW discharge power. 900 mA of this beam are then delivered to a remote target within 20 mrad divergence half-angle [32].



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As a general remark, it appears to be more difficult to design a properly working two-stage discharge ion source than, for example, a multicusp source, but once having succeeded with this task, there is the benefit of the higher efficiency as compared to other sources. Moreover, a special operating mode becomes possible where a protective gas is fed into the first chamber, impeding fast consumption of the filaments, and a reactive gas into the second chamber, where no more hot metal electrodes are present. This two-gas technique [29] allows the stable production of many interesting ion species such as from high-melting-point elements. One has to take into account, however, that the desired ions have to share the total beam current with other species, and their fraction typically lies in the order of 15%. For oxygen, using argon and pure oxygen gas, 138 mA dc O_1^+ ions—552 (mA) normalized—out of 250 mA total current were obtained from 1.4 cm^2 outlet aperture at 52 kV, running a duopigatron at 1.25 kW discharge power [33].

In pursuing the idea of a two-stage discharge one could also go a step further and combine an rf discharge as first stage with a reflex chamber, lined with permanent magnets or equipped with a diverging axial field, to completely avoid any cathode erosion but still have the good efficiencies, wide range of operation parameters, and homogeneity found with stationary discharges.

3 MULTIPLY CHARGED IONS

The plasma generators presented in this chapter do not generally lend themselves to a copious production of multiply charged ions. This is partially due to the requirements listed earlier: In optimizing a discharge toward generating a quiet, cold plasma, one automatically ends up at conditions where singly charged ions are being produced preferentially. Further, when looking for maximum beam brightness values, one would hardly like to share the beam current among different ion charge states, but this is a necessary condition associated with steady state formation of multiply charged ions.

However, in cases where the highest brightness values are not the predominant requirement for a source, multiply charged ions might still be of interest, and there are some investigations of this topic being carried on presently. The most prominent results have been obtained with multicusp sources: In one experiment using an argon plasma and 250 V discharge voltage traces of Ar^{7+} were found [34], and in another experiment the following beam currents for multiply charged ions have actually been transported [35]: 11.6, 10.2, 5.0, 2.2, 0.8, and 0.11 mA for Xe^+ through Xe^{6+}, and 15.8, 9.9, 3.4, 0.44, 0.16, and 0.06 mA for Kr^+ through Kr^{6+} (both electrical, not particle currents). To obtain these values, the discharge had to be run at 400 V and 58 A, and such power loads imply pulsed operation with duty factors below 25%.

It is interesting to note that with the same source and extraction system that yielded the multiply charged ions listed above the discharge current was lower by a factor of three when a maximum share of singly charged ions was being produced. Considering that the plasma density must be equal in both cases to match the

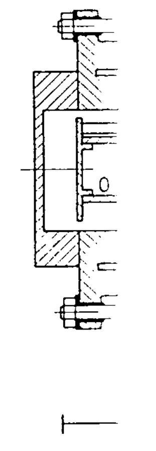
identical extraction field strength, one can conclude that at least the electron temperature, and most probably the ion temperature as well, is higher by about a factor of 10, compared to the normal values, when the discharge is tuned to favor the generation of multiply charged ions. Such a trend would further inhibit the formation of maximum-brightness beams, in addition to the facts mentioned above.

4 IONS FROM ELEMENTS WITH LOW VAPOR PRESSURE

General hints regarding the processing of nonvolatile elements in ion sources were published some time ago [36]. The most universal approach is to use volatile compounds, such as chlorides, fluorides, or in some cases oxides and sulfides. On-line chlorination techniques, guiding a flow of Cl_2 or CCl_4 over the solid material of interest, can also give good results in some cases. But there are three major drawbacks associated with these techniques. First of all, the total beam current has to be shared among different ion species, that is, the main components of the compound and usually a series of different molecular ions. The exact distribution depends on the chemical equilibrium in the discharge plasma and cannot be known in advance. Second, all the mentioned compounds have reactive constituents, and their use will shorten the filament lifetime considerably for all sources with steady discharges and thermionic cathodes. Employing a two-gas technique, as described in the section on two-stage discharges, will only partially solve this problem. And third, one must take care to prevent condensation of the nonvolatile constituent on cold source walls, which will occur whenever a compound preferentially dissociates before being ionized.

Thus, hot walls inside a source are very useful in any case, and the two well-established ways to realize them are either by using a discharge chamber made from graphite [37] or by installing metal liners inside a cold chamber [38]. In both cases, the radiation from the cathode filaments will keep the walls hot, independently of the discharge power that may not be distributed uniformly over the wall surfaces.

From a discharge chamber with hot walls it is only a small step to a source with incorporated oven, to produce vapors from pure elements. As an example of such a source, the hot version of the multicusp/reflex discharge CHORDIS [22], mentioned above, is shown in Figure 7.10. It can deliver the same ion current values as the cold basic version, and additionally permits processing any material with more than 2 Torr vapor pressure at 1000 °C. As a precaution, however, the extraction gap has to be made wider than the minimum value for operation with gases only, see the chapter on Ion Extraction, and this leads to a decrease of beam current and brightness. For bismuth, a dc ion current of 37 mA—535 (mA) normalized—was obtained from 2 cm^2 outlet aperture at 36 kV, with as little as 340 W discharge power, due to the low ionization energy of the metal. Adding an auxiliary gas such as argon to the vapor appears to be helpful in getting a stabler discharge, but still the ion beam contains as little as 5 to 10% gas ions, because their ionization energies are considerably higher than those of metals.



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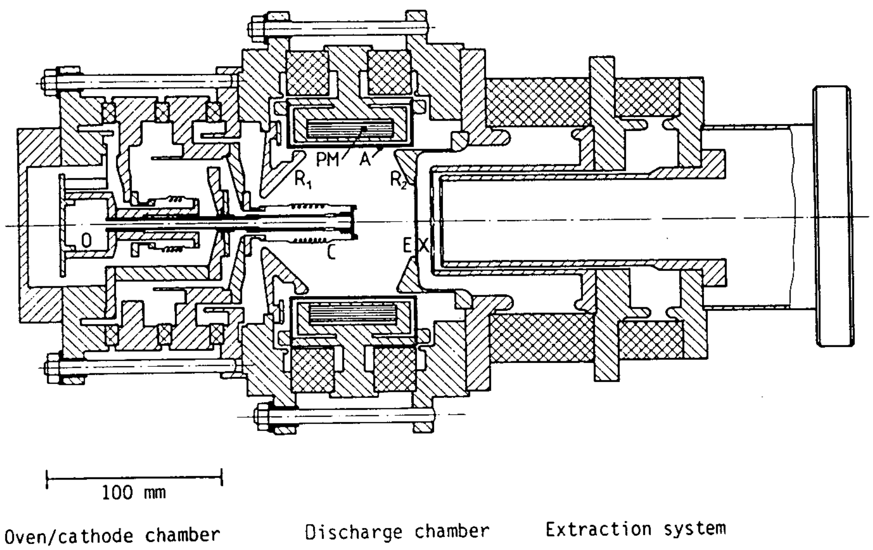

Figure 7.10 Hot version of CHORDIS, with integrated oven [Ref. 22]. A, hot-running anode; C, cathode filament; EX, accel-decel extraction system; PM, permanent magnet; R_1, R_2, reflector electrodes; R_2 acts as outlet electrode as well; O, oven, to be charged from the back side of the source. The vapor is transported through a pipe from the oven to the cathode support tube and flows radially into the discharge chamber. The beam is extracted to the right.

The relatively low ionization energies of metallic elements are also advantageous when using a sputtering technique, well known from other ion source types such as the PIG [39] or Duoplasmatron [40]. In this case, an auxiliary discharge with one of the heavier noble gases is sustained in the source, and an electrode covered by the metal of interest is biased to some hundred volts negative with respect to the anode. This potential attracts ions from the discharge plasma, and they sputter atoms away from the surface; these will then be ionized by the discharge. The sputtering technique can, in principle, be applied to all metals, even those with low vapor pressures, and in the form of powder mixtures with metals pressed into shape, nonconducting materials can be processed, too. The particle production rate can easily be controlled through the current drawn by the sputter electrode, and this electrode should be well cooled, to avoid runaway conditions. As a demonstration of this technique, applied to a high-current ion source, an experiment has been performed using a modified CHORDIS where the outlet electrode was covered by an aluminum ring and electrically insulated against the other reflector electrode. A share of 20% aluminum ions was reached in the extracted beam at 250 V sputter voltage, using argon as auxiliary gas [41]. For elements with lower sputtering coefficients [42], shares in the 10% range can be expected.

Following experience with PIG sources for multiply charged ions [43], the internal parts of a sputtering high-current ion source should be kept hot to avoid recondensation of the material of interest, in the same way as when using volatile

chemical compounds. The advantage of the sputtering technique lies in the fact that the use of reactive materials can be completely avoided.

5 OUTLOOK

A description has been presented of the basic physical working principles of gaseous, high-current sources, including some special topics such as multiply charged ions and low vapor pressure elements. This is intended as an introduction to the field, however, and is not meant to enable newcomers to start building the ion source of their choice right away without further research. But at least the fundamentals will now rest on a solid foundation.

One important aspect of ion source design has been almost completely omitted in this brief overview: the technological point of view. Besides the physical principles discussed, the problems of vacuum, insulation, high voltage, high temperature, and power dissipation problems have to be addressed at the same time. The reader should refer to the literature for in-depth accounts of how these problems have been solved in different situations. For this purpose, not only the publications concerned with individual sources—as quoted in the text—are recommended, but also more general ones [36, 45]. In addition, the reader will without doubt find much valuable information in the conference proceedings of Vienna [45], Kyoto [46], and a conference series in Great Britain [47, 48]. Basic material properties, without direct connection to ion sources, are collected in Refs. 49 and 50.

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